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Brillouin light scattering study of spin waves in NiFe/Co exchange spring bilayer films

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Spin waves are investigated in Permalloy($Ni_{80}Fe_{20}$)/Cobalt(Co) exchange spring bilayer thin films using Brillouin light scattering (BLS) experiment. The magnetic hysteresis loops measured by magneto-optical Kerr effect show a monotonic decrease in coercivity of the bilayer films with increasing Py thickness. BLS study shows two distinct modes, which are modelled as Damon-Eshbach and perpendicular standing wave modes. Linewidths of the frequency peaks are found to increase significantly with decreasing Py layer thickness. Interfacial roughness causes to fluctuate exchange coupling at the nanoscale regimes and the effect is stronger for thinner Py films. A quantitative analysis of the magnon linewidths shows the presence of strong local exchange coupling field which is much larger compared to macroscopic exchange field. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4870053]

I. INTRODUCTION

The exchange spring systems are constituted by hard and soft magnetic thin films, which are exchange coupled at their interface.[1,2] They have been found to display characteristic structure in the magnetic hysteresis properties with enhanced remanent magnetization and coercivity. The high saturation magnetization of the soft magnetic material and the high coercivity of the hard magnetic material improve the maximum energy product.[3–5] It makes the exchange springs potential candidate for applications as permanent magnets and recording media.[6–8] The exchange coupling behavior depends on the thickness of the soft magnetic material. When the thickness of the soft magnetic layer is small then the system behaves as a rigid magnet while for its higher thickness the system behaves as an exchange spring magnet. Therefore, the magnetic behaviors of the system are strongly influenced by the soft layer thickness, which allows the existence of three different magnetic regimes: the hard single-phase, the exchange coupled regime, and the exchange decoupled regime. For all these behaviors, a decrease of coercivity is expected by increasing the soft layer thickness.[5,9] However, in few cases an initial increase of coercivity has been observed.[7,10] Understanding of surface and interface magnetism in exchange spring multilayers are crucial to finely tailor their properties. One of the proven methods for this is to probe spin waves as they are sensitive to exchange coupling and other effective fields in magnetic multilayers. Therefore, spin wave excitations in such systems reveal interlayer exchange, anisotropy energies and other important parameters. Spin wave investigations by light scattering experiments were reported in exchange coupled systems, e.g., Co/CoPt,[11,12] FeTaN/FeSm/FeTaN,[13] Co/Pd-NiFe.[14] On the other hand, time-resolved magneto-optical Kerr effect measurements on FePt/NiFe exchange spring bilayers showed a strong variation in spin wave mode frequencies with variation of NiFe layer thickness due to the variation of exchange field and the ensuing spin twist structure in the NiFe layer.[15] Theoretical modelling of the spin twist structures in exchange spring systems and coupled multilayers have also been presented by several authors.[16–18]

In this work, we report the Brillouin light scattering (BLS) study in $Ni_{80}Fe_{20}$ (Py)/Co exchange spring bilayer systems with varying Py layer thickness. As opposed to the previous reports on magnetization dynamics in Py(50 nm)/Co(100 nm) bilayer films[19,20] we have used much thinner ferromagnetic layers and attempted to increase the anisotropy of the Cobalt layer by elevating the substrate temperature during deposition to assist greater differences in magnetic parameters of the constituent layers of the exchange spring bilayer system. Here, we have addressed the phenomena occurring at the soft/hard interface and their relation with the magnetic properties of the system, such as the degree of soft/hard exchange coupling and the coercivity behavior as a function of the Py film thickness.

II. EXPERIMENTAL DETAILS

The Py/Co bilayers were grown by dc magnetron sputtering onto self-oxidized silicon [100] substrates at 2×10^{-8} Torr base pressure. First, a 10 nm Co layer was deposited from a Co target (99.99%) at a substrate temperature of 500 °C. The optimum value of the substrate temperature for the Co layer was determined by a careful investigation of the substrate temperature dependence of its coercivity. Py layers with thickness varying between 10 and 30 nm were then grown at room temperature from Py target (99.99%) on the Co layer. All depositions were performed at working pressure of about 10 mTorr and at a dc power of 400 W for Co and 350 W for Py. The topography and roughness of the films were measured by atomic force microscopy (AFM). The quasistatic magnetization reversal properties were measured using a longitudinal magneto-optical Kerr effect

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(MOKE) magnetometer using a He-Ne laser operating at 632.8 nm. Thermal magnons were measured in these bilayer films using BLS technique to investigate the role of interfacial exchange coupling (J_I). BLS is a powerful technique for the investigation of spin waves in magnetic thin films (transparent or opaque), multilayers, and patterned magnetic structures.[21–23] This technique relies on inelastic light scattering process due to interaction between incident photons and magnons. Magnons are created or annihilated during the interaction with photons. A frequency shift is observed along with the laser frequency taking into account energy and momentum conservation. The BLS experiments were performed in backscattering geometry using a single-mode solid state laser operated at 532 nm (wave number $k_i = 1.181 \times 10^5$ rad/cm) and a Sandercock-type six-pass tandem Fabry-Perot interferometer. It enables wave vector resolved measurements of the spin waves by changing the angle of incidence (θ) of the laser beam.

III. RESULTS AND DISCUSSIONS

In Fig. 1, AFM images show that the Py/Co bilayer films are continuous. It consists of interconnected grains with average grain size of 10–20 nm and the sample roughness of the film varies between 1.7 and 3.1 nm with increasing Py film thickness. The surface consists of an arrangement of homogeneously distributed islands which has been formed during the intermediate growth state. The islands are not well separated but seem to be connected due to coalescence.

The room temperature MOKE hysteresis loops measured within a laser spot size of about 50 μm from the Py/Co bilayer films are shown in Fig. 2. The coercivity (H_C) of the Py(t)/Co(10 nm) films varies systematically as 435, 335, 159, and 132 Oe for $t = 10$, 20, 25, and 30 nm, respectively. We mentioned earlier that we intended to enhance the H_C value of Co base layer by optimizing substrate temperature. Significant increase in H_C is found in the Co single layer film deposited at around 500 °C substrate temperature ($H_C = 727$ Oe) as compared with the Co film deposited on a substrate at room temperature ($H_C = 243$ Oe). The enhanced coercivity of the Co layer in combination with its greater saturation magnetization and exchange stiffness constant is expected to have a greater influence on the exchange spring behaviour of the bilayer samples. We observe that bilayers

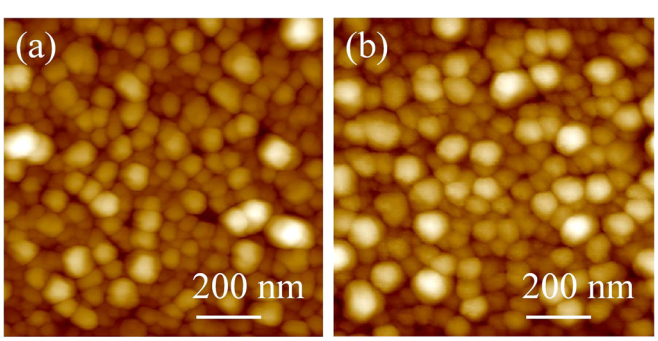

FIG. 1. AFM images of (a) Py(10 nm)/Co(10 nm) and (b) Py(20 nm)/Co(10 nm) bilayer films.

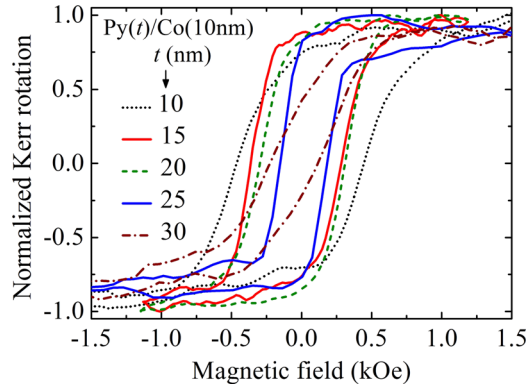

FIG. 2. Magnetic hysteresis loops for all the Py(10–30 nm)/Co(10 nm) bilayer films measured with static MOKE experiment.

with Py layer thickness ≤ 25 nm have a more square-like hysteresis loop and the squareness suddenly decreases for Py layer thickness >25 nm. The laser spot penetrates about 12 nm (optical skin depth) down from the surface of the Py layer and thus, the MOKE data indicates that the top 12 nm of the Py layer is strongly exchange coupled with the Co layer for Py layer thickness up to 25 nm and beyond that the coupling becomes weaker. The coercive field of the Py(30 nm)/Co(10 nm) bilayer is 132 Oe, which is still much greater than a single Py layer, ensuring a significant contribution from the Co layer for the sample with a Py as thick as 30 nm.

We have further studied thermally excited magnons to understand the effect of the interfacial exchange coupling in our exchange spring bilayers. Figure 3 shows the field dependence of BLS spectra for Py(25 nm)/Co(10 nm) sample. A bias magnetic field (H) was applied in the plane of the film and the angle of incidence (θ) was chosen as 45°, which results in a magnon wave number $k_{||} = 2k_i \sin\theta = 1.67 \times 10^5$ rad/cm. The BLS spectra reveal two distinct peaks in the bilayer films. Optical and acoustic spin wave modes were observed previously in a thicker bilayer film Py(50 nm)/Co(100 nm) by Crew *et al.*[20] However, our observed modes have different origin. The peak (−2.7 GHz) near zero frequency is due to measurement artifact.

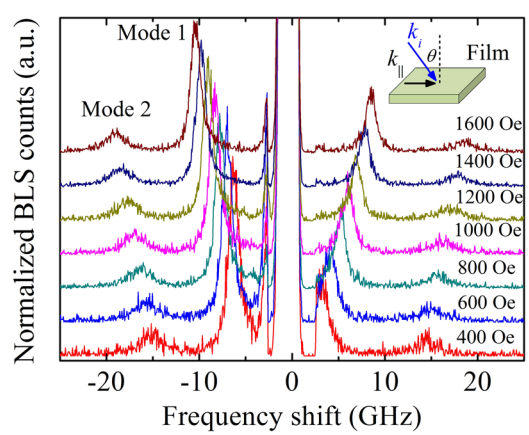

FIG. 3. BLS spectra for Py(25 nm)/Co(10 nm) film at different in-plane bias magnetic fields. Angle of incidence is $\theta = 45°$. The measurement geometry is shown in the inset.

Further measurements reveal that the lower frequency mode has a pronounced dispersion with the in-plane wave vector ($k_{||}$) and it corresponds to the surface wave, which propagates in the film plane (Damon-Eshbach mode). On the other hand, negligible dispersion with $k_{||}$ is observed for the higher frequency mode and it is identified as the volume mode, which propagates perpendicular to the surface of the film, also known as the perpendicular standing spin wave (PSSW). Experimental dispersion results of these two modes are shown in one of the insets of Fig. 4. The bias field dependences of the two modes are shown in Fig. 4. Frequency of the lower mode becomes very small in low field regime (<200 Oe) and could not be reliably detected using the BLS experiment. Therefore, we concentrated on the higher frequency mode or the PSSW mode for field hysteresis in the low field regime from positive (all layers along the field direction) to negative field direction and it is shown in another inset of Fig. 4. A minimum of the frequency was observed at −25 Oe during the field hysteresis, which is a signature of the presence of an exchange coupling between the layers. For fields above −25 Oe the magnetization of the bilayer is parallel with the field direction. Therefore, a quantitative analysis for the bias field dependence of the surface wave frequency can be made by incorporating an effective exchange field (H_{ex}) in H as $H_{eff} = H + H_{ex}$. The data were analyzed following the approach of Rezende *et al.*[24] The authors have extended the theory of two magnon scattering by Arias and Mills[17] for non-zero wave vector ($k \neq 0$) magnons. Neglecting uniaxial anisotropy field, the frequency of the magnons is given by

$$f = \frac{\gamma}{2\pi}\left\{\left(H_{eff} + 2\pi M_S k_{||} t \sin^2\varphi + \frac{2A}{M_S}k_{||}^2\right) \times \left(H_{eff} + 4\pi M_{eff} - 2\pi M_S k_{||} t + \frac{2A}{M_S}k_{||}^2\right)\right\}^{1/2}, \quad (1)$$

where γ, M_S, A, and φ are the gyromagnetic ratio, saturation magnetization, exchange stiffness constant of Py film, and the angle of magnon wave vector in the film plane, respectively. Gyromagnetic ratio is connected to magnetomechanical ratio g by $\gamma = g\mu_B/\hbar$, where μ_B is the Bohr magneton and $\hbar$ is the reduced Planck constant. Surface anisotropy (H_S) is included in the effective magnetization (M_{eff}) as $4\pi M_{eff} = 4\pi M_S + H_S$. For $\varphi > \varphi_C$, where the critical angle $\varphi_C = \sin^{-1}\sqrt{H/(H + 4\pi M_S)}$, the spin waves are surface waves whereas for $\varphi < \varphi_C$ they are volume waves. The critical angle, in our case, is found to be 26° for $H = 1600$ Oe. The data are fitted with Eq. (1) using $t = 25$ nm, $A = 1.3 \times 10^{-6}$ erg/cm, and $4\pi M_S = 10.053$ kG for Py while leaving M_{eff}, g, *and* φ as fitting parameters. The fitting yields $g = 2.15$, $\varphi = 33°$, and $4\pi M_{eff} = 5.353$ kG. Larger g values have been observed before and can be explained by taking the bottom Co layer into account,[25] while other parameters have reasonable values. We should mention here that the intensity of the magnon modes decreases with increasing magnetic field and the effect is more pronounced for the low frequency modes compared to the higher frequency modes discussed here. It is also in agreement with the previous observations.[20] The PSSW mode forms along the thickness of the bilayer film and is therefore sensitive to both the parameters for Py and Co layers in the Py(25 nm)/Co(10 nm) bilayer. Spin configuration varies across the bilayer and a rigorous theoretical model including the spin twist structure will be required for detailed analysis. Nortemann *et al.* have proposed a semi-classical numerical model for understanding the spin wave frequencies in this type of systems.[16] A qualitative analysis has been performed here assuming the bilayer as an effective single medium with a characteristic effective exchange constant (A') and saturation magnetization (M'_S). Subsequently, a model for the PSSW mode is deployed for that single layer film. Although this approach is based on coarse assumptions but it may provide useful and quick information about the long wavelength spin wave energies and the effect of the two coupled layers in a bilayer film.[26] Neglecting uniaxial anisotropy field, the frequency of the PSSW magnons is given by[27]

$$f = \frac{\gamma}{2\pi}\left\{\left(H_{eff} + \frac{2A'}{M'_S}k_\perp^2 + \frac{2A'}{M'_S}k_{||}^2\right) \times \left(H_{eff} + 4\pi M_{eff} + \frac{2A'}{M'_S}k_\perp^2 + \frac{2A'}{M'_S}k_{||}^2\right)\right\}^{1/2}. \quad (2)$$

Here, $k_\perp$ is the wave vector perpendicular to the surface of the film defined as $k_\perp = n\pi/t$, where n represents the PSSW mode number and t is the thickness of the bilayer. For the data in Fig. 4, we have used $t = 35$ nm, $k_{||} = 1.67 \times 10^5$ rad/cm, and $g = 2.15$, while M'_S, A', and M_{eff} are used as fitting parameters in Eq. (2). The fit yields, $4\pi M'_S = 12.202$ kG, $A' = 1.76 \times 10^{-6}$ erg/cm, and $4\pi M_{eff} = 4.046$ kG. Interestingly, the value of the exchange constant is close to the weighted average of the exchange constants of the two layers which is $A' = (t_{py}A_{Py} + t_{Co}A_{Co})/(t_{py} + t_{Co})$. A similar result is also observed in the case of M'_S value. The effect of coupling between the Py and Co layers is clear from this qualitative picture. A detailed analysis will be of future interest.

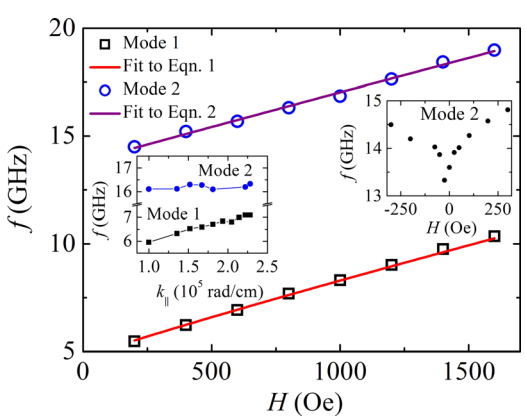

FIG. 4. Spin wave frequencies of mode 1 and mode 2 as a function of magnetic field for Py(25 nm)/Co(10 nm) film (symbols) along with the fits (line). Dispersions (f ($k_{||}$)) of the two modes have been shown in one of the insets. The symbols correspond to the experimental data while the lines joining the symbols are only guide to the eyes. Other inset shows the field hysteresis of mode 2 in low field regime.

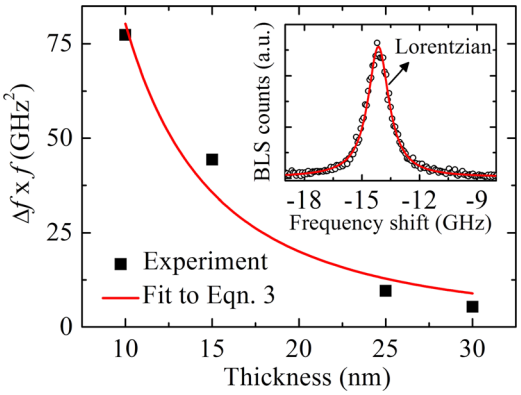

FIG. 5. Thickness dependence of $\Delta f \times f$ for Py(t)/Co(10 nm) films (symbols). A fit to Eq. (3) has also been shown (line). Inset shows the Lorentzian fit to experimental BLS spectrum obtained for Py(25 nm)/Co(10 nm) film at $H = 2800$ Oe.

We further noticed that the BLS linewidths (Δf) of the frequency peaks (f) increase significantly with decreasing Py layer thickness. Interfacial roughness may cause the exchange coupling to fluctuate at the nanoscale regime and the effect is stronger for thinner Py films.[28] This may broaden the linewidths of spin wave peaks as observed in our experiment. We have shown the variation of $\Delta f \times f$ as a function of Py thickness (t) in Fig. 5. Magnon linewidths and peak positions were calculated by fitting the peaks with Lorentzian function (inset of Fig. 5). We have extracted the coupling parameter from the magnon linewidth ($k > 0$) expression as given below[28]

$$\Delta f = \frac{\gamma^2 p \langle A_d \rangle \langle \cos^2\alpha \rangle 4\pi M_S \xi}{2\pi D f} \left(\frac{J_I}{M_S t}\right)^2. \quad (3)$$

Here, p is fraction of defects, $\langle A_d \rangle$ is the surface area, α is the angle between the moments of the two layers, ξ is a numerical factor, $D = 2A/M_S$, and J_I is the interfacial exchange energy. We fit the data in Fig. 5 with Eq. (3) by assuming estimates from AFM data as $p = 0.3$, $\langle A_d \rangle = 20$ Å^2, while $\langle \cos^2\alpha \rangle$ is assumed as 0.5. Numerical factor ξ may have small variation with film thickness but assumed as a constant in fitting for simplicity with an average calculated value of 0.55. J_I is left as a free parameter. The fit yields $J_I = 9.39$ erg/cm^2, which is equivalent to a local exchange coupling field $H_I = J_I/M_S t = 4.69$ kOe for the bilayer with 25 nm Py thickness. This local field is much larger compared to the macroscopic field obtained from the experiment as the measurements are done within about 12 nm from the surface of the film and the exchange field drops exponentially from the interface as it penetrates within the Py layer.

IV. CONCLUSIONS

In summary, Brillouin light scattering technique was applied to investigate exchange coupling behavior in Py/Co bilayer films. Coercivity of the bilayer films systematically decreases with increasing Py layer thickness. The coercivity behavior of the bilayers as a function of the deposited Py layer strongly depends on both the mechanism controlling the moment reversal and the phenomena occurring at the soft/hard interface. BLS spectra show the presence of surface and volume modes. Exchange coupling behaviour is clearly observed from their analyses as a function of magnetic field. A model based on two magnon scattering is used to quantitatively analyze the linewidths of the spin waves from different bilayer films and interfacial exchange coupling parameter was deduced. Local exchange field was found to be much larger in comparison with measured macroscopic value.

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